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Ecosystem services in life cycle assessment: A synthesis of knowledge and recommendations for biofuels

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ABSTRACT

There is an increasing trend in promoting the use of biofuels for transportation as a low-fossil carbon energy source, but little knowledge on their multidimensional environmental impacts. Whole-system approaches, such as life cycle assessment (LCA), have been extensively employed to analyze the environmental performance of different biofuels. However, it remains unclear to which extent biofuels impact ecosystems and the services they provide, in particular related to different management practices. To overcome this challenge, this paper draws recommendations to better holistically address ecosystem services (ES) in LCA, with a focus on biofuels. We first pinpoint some of the challenges in accounting for the concept of ES in decision-making and review some of the existing ES classification frameworks and the usefulness of the cascade model. Second, we discuss the implications of identified context-specific aspects on the modeling of biofuel production impacts on ES in LCA. Finally, we propose a conceptual framework to link ES classification systems, the cascade model and the LCA approach. Although some challenges still remain unsolved, due to the existing life cycle impact assessment structure, existing ES frameworks and the cascade model are helpful tools to better include ES into LCA of different biofuels.

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1. Introduction

Climate change mitigation is high on the agenda in numerous national and international policy decisions and action plans, particularly in relation to the transportation sector (IPCC, 2014). There is a strong political pressure towards an increased large-scale

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production and use of biofuels, in order to promote the transition from a fossil-based economy to a more sustainable society (EC, 2012; IPCC, 2012; Johnson et al., 2012). For instance, the European Union (EU), in its EU Renewable Energy Directive (EU-RED), defined a set of mandatory sustainability criteria for biofuels used in transportation – and liquid biofuels for other energy purposes – with the aim to reduce levels of greenhouse gas emissions from its member states (EU, 2009). Furthermore, the EU has imposed restrictions in order to mitigate risks related to areas of high biodiversity value. Yet, a comprehensive list of potential negative impacts of biofuel production on ecosystem services (ES) is not addressed in the sustainability criteria in the EU-RED.

Although there is a growing trend towards using feedstock that require less land area, such as sea-based and residue-based biofuels (Alvarado-Morales et al., 2013; Demirbas and Demirbas, 2011), the largest share of the liquid biofuels produced worldwide is based on biomass produced on farmland (Bringezu et al., 2009; Groom et al., 2008). Albeit the potential positive contributions to climate change mitigation and renewable fuel supply, this production is generally associated with the expansion of land areas and/or an increase in crop yield. In a similar manner, wood-based bioenergy represents a significant share of energy production in Europe and North America, having impacts on forest ecology and recreation (Solberg et al., 2014). Evidence suggests that the increased production of biofuels hampers ecosystem processes and leads to habitat disruption and fragmentation as well as decreased levels of species richness (Fargione et al., 2010; Joly et al., 2015; Koh, 2007). Biofuel production may further impact important ES, such as provisioning (e.g. food supply), supporting (e.g. habitat provision), regulating (e.g. freshwater regulation), and cultural services (e.g. aesthetic values) (Gasparatos et al., 2011; Holland et al., 2015). This demonstrates the complex impacts of biofuels on overarching environmental sustainability.

The recognition of nature's value and the holistic understanding of ecosystem functions are core conditions for broad-gauge sustainability assessments. In this context, outstanding global efforts (MA, 2005; TEEB, 2010) and several studies (Corbière-Nicollier et al., 2011; Costanza et al., 1997; de Groot et al., 2002; van Oudenhoven et al., 2012) perceived the need to advance knowledge in understanding the linkages between ecosystem functions and services provided to human beings. These initiatives also laid the ground to establish a solid scientific basis for actions to improve environmental conservation and sustainable use of natural resources. For instance, in order to tackle the increasing loss of ES, there is the need to understand the impacts of biofuel feedstocks on ecosystems and to grasp the synergies and the trade-offs between biofuel production and the different ES impacted. Therefore, all-embracing assessments, set to evaluate which services are mainly affected during the production of biofuels, could draw more precise conclusions about the overall sustainability of different fuel options. Such an approach was taken by Gasparatos et al. (2011) when discussing the impacts of the production of first generation biofuels on ES. Holland et al. (2015) made a similar effort, by synthesizing the implications of second generation bioenergy crop production for a range of ES. However, they stressed that there is still a knowledge gap on the effects of biofuel production on ES and how these effects should be accounted for in policy-making. For that purpose, both an in-depth understanding of different aspects influencing biofuel production and a review of current mechanisms for the integration of ES in decision-support tools are needed.

The purpose of this paper is to identify and discuss the main aspects to be considered when implementing the ES concept into decision-making tools, such as life cycle assessment (LCA), with a focus on the current state-of-the-art of the assessment of ES influenced by biofuel production. First, we synthesize the current knowledge on main existing classification frameworks that set the scene for ES. Second, we review context-specific aspects to be considered when implementing the ES concept into decision-making related to biofuel production. Third, we discuss existing gaps that hinder the assessment of impacts on ES in LCA, with a particular focus on biofuel production. Finally, we argue how an ecosystem classification framework may be helpful in addressing impacts of ES on LCA. The learnings we obtain are not restricted solely to the biofuel production, but may well be extended to other land-related activities (e.g. livestock production).

2. Ecosystem services in decision-making

It is widely accepted that the concept of ES does not exist in isolation from human-beings' needs (Haines-Young and Potschin, 2010), yet no well-established definition is available (Patterson and Coelho, 2009). In this paper, we chose to work with the definition by which the term ES denotes the benefits (goods and services) human beings directly and indirectly obtain from ecosystems (Daily, 2000; Fisher et al., 2009; MA, 2005).

Understanding the extent to which human society, in all its complexity, affects ES is not an easy task. First, ecosystems are complex and dynamic systems, and the interactions between their functions, processes and services are still poorly understood (de Groot et al., 2010; Kremen, 2005; Yang et al., 2013). An estimation of the functions ecosystems provide requires an in-depth knowledge of different aspects related to ecology (Boyd and Banzhaf, 2007), as well as the consideration of local and regional context (Efroymson et al., 2013). Second, ecosystems usually deliver multiple services, that interrelate in intricate ways, across space and time, and synergies and trade-offs among different services may occur (Bastian et al., 2013; Costanza et al., 2011; Rodriguez et al., 2006). Third, ES assets are rarely monitored (Daily et al., 2009; Gasparatos et al., 2011), mainly as a result of the intricacy in data gathering and the difficulty in tracking supplies and demands of these services (Burkhard et al., 2012). Finally, the concept of ES is evolving, embedded within the human society's understanding of nature's complexity and value (Daily, 2000).

Several challenges stem from this complexity, as how to map and assess ES. This task becomes even more imperative when the implementation of ES classification is intended for decision making (Burkhard et al., 2012; Naidoo et al., 2008). In order to characterize the interactions between human activities and ecological systems and to understand the trade-offs amongst multiple services (Abson et al., 2014; Burkhard et al., 2012; Rodriguez et al., 2006), substantial efforts have been devoted to quantify ES at multiple scales (Bennett et al., 2009; Nelson et al., 2009; Power, 2010; TEEB, 2010; Yang et al., 2013) and several classification frameworks of ES have been developed in recent years.

Three main global analytical frameworks are available to assess ES: the Millennium Ecosystem Assessment (MA, 2005), The Economics of Ecosystems and Biodiversity (TEEB, 2010) and the Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2013). However, a range of other classification and accounting systems for ES have emerged after the MA, with the objectives of avoiding double counting, including a broader range of services, and economic accounting. We briefly describe and discuss pros and cons of these frameworks addressing ES, as well as their capacity to translate scientific information into knowledge that may be easily interpreted by stakeholders in decision-making (Table 1).

The *Millennium Ecosystem Assessment* (MA) developed a conceptual framework providing the scientific basis and a wider understanding to recognize the linkages between ES and human well-being at multiple scales (Dick et al., 2011; Reid et al., 2006). The

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